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FULL PAPER

Reduction of radiation exposure by lead curtain shielding in dedicated extremity cone beam CT

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Objective: A dedicated extremity cone beam CT (CBCT) was introduced recently, and is rapidly becoming an attractive modality for extremity imaging. This study aimed to evaluate the effectiveness of a curtain-shaped lead shielding in reducing the exposure of patients to scattered radiation in dedicated extremity CBCT.

Methods: A dedicated extremity CBCT scanner was used. The lead shielding curtain was 42×60 cm with 0.5-mm lead equivalent. Scattered radiation dose from CBCT was measured using thermoluminescence dosimetry chips at 20 points, at different distances and directions from the CT gantry. Two sets of scattered radiation dose measurements were performed before and after installation of curtain-shaped lead shield, and the percentage reduction in dose in air was calculated.

Results: Mean radiation exposure dose at measured points was $34.46 \pm 48.40 \mu\text{Gy}$ without curtains and $9.67 \pm 4.53 \mu\text{Gy}$

with curtains, exhibiting 71.94% reduction ($p = 0.000$). The use of lead shielding curtains significantly reduced scattered radiation at 0.5, 1.0 and 1.5 m from the CT gantry, with percent reductions of 84.8%, 58.0% and 35.5%, respectively ($p = 0.000$, 0.000 and 0.002). The percent reduction in the diagonal ($+45^\circ$, -45°) and vertical forward (0°) directions were 86.3%, 83.1% and 77.7%, respectively, and were statistically significant ($p = 0.029$, 0.020 and 0.041).

Conclusion: Shielding with lead curtains suggests an easy and effective method for reducing patient exposure to radiation in extremity CBCT imaging.

Advances in knowledge: Lead shielding curtains are an effective technique to reduce scattered radiation dose in dedicated extremity CBCT, with higher dose reduction closer to the gantry opening.

Plain radiographic examinations are routinely used in initial evaluation of bony injuries, but superimposition of structures and other inherent problems associated with this technique cause misdiagnosis.¹ CT is widely used for more detailed evaluation of suspected injuries in extremities. Multidetector CT (MDCT) can provide medical practitioners with detailed morphological information on osseous and soft-tissue structures.

More recently, cone beam CT (CBCT) has been introduced for extremity imaging.² This application offers an attractive alternative with high spatial resolution, which enables detailed visualization of osseous structures, easy installation owing to its smaller size, and relatively low radiation dose compared with conventional MDCT scanners.^{3–7} There are an increasing number of papers reporting various clinical applications of CBCT, such as in CT angiography and in weight-bearing imaging.^{8,9} Like other imaging modalities using ionizing radiation, reducing patient radiation dose is an important issue.¹⁰ Patient radiation exposure can be largely categorized into the following two categories:

(1) radiation dose within the field of view (FOV) and (2) scattered radiation extending beyond the FOV area. Although radiation dose within FOV has been a major concern regarding patient dose, we cannot neglect the out-of-field radiation that can affect radiosensitive organs such as the gonads and the thyroid gland in extremities imaging.

Several approaches exist for reducing scattered radiation, including decreasing the overall radiation dose by adjusting the radiation source and shielding. Decreasing radiation exposure dose within FOV results in reduced out-of-FOV radiation because scattered radiation is positively correlated to the entrance surface dose.¹¹ However, a certain amount of radiation dose is necessary within the FOV for maintaining image quality. Therefore, there are limitations on reducing the scattered radiation by adjusting the radiation source. Shielding materials can be placed between the radiation source and the areas where protection is needed for further reducing the out-of-field radiation. Various methods have been developed

Figure 1. Schematic drawing of cone beam CT equipped with lead curtains. A pair of lead curtains were installed in front of the gantry opening, as well as on the opposite side. All units given in millimetres.

for reducing the scattered radiation, for example, lead apron, lead shield and radio-absorbable drape in the setting of fluoroscopy-guided procedures.^{12,13} However, there are no

standardized methods for reducing the scattered radiation to patients in extremity scanning using mobile dedicated extremity CBCT.

Figure 2. Positions of measurement points (dots), according to their distance and direction. Distances and directions were measured relative to the cone beam CT isocentre.

Figure 3. Photographs of the dedicated extremity cone-beam CT before shielding with lead curtains (a) and after applying the lead curtains (b).

(a)

(b)

Therefore, we proposed a curtain-shaped radiation-absorbing material hung at the gantry outlet. The goal of this study was to evaluate the effectiveness of curtain-shaped lead shielding

technique for reducing the radiation exposure in dedicated extremity CBCT.

METHODS AND MATERIALS

A dedicated mobile volumetric CBCT scanner (PHION®; NanoFocusRay Co. Ltd, Jeonju, Republic of Korea) was used in this study (Figure 1). A standardized scan protocol with 130 kVp of tube voltage and 8 mA of tube current was applied. A scan took 5.4 s, and an effective tube current was 21.6 mA. For simulating the upper extremity scan, an elbow phantom (RS-120T®; Radiology Support Devices Inc., Long Beach, CA) was placed in the CT isocentre.

Thermoluminescence dosimetry (TLD) chips (TLD-200®; Thermo Fisher Scientific, Waltham, MA) were placed at 20 points at the same height as the gantry centre, which is 85 cm above the ground (Figure 2). A vertically drawn line from the CT isocentre, along the z-axis, in the forward direction, was set as 0°. Five directions with 45° angle were selected: 0°, 45° to the right (+45°), 90° to the right (+90°), 45° to the left (−45°) and 90° to the left (−90°). For each direction, four measurement points were chosen with a 0.5-m interval, from 0.5 to 2.0 m. At each measurement point, three TLD chips, each labelled, were placed in a fixed array. To reduce the effect of radiation scattering by materials that support the TLD chips, a thin thread was used to support the TLD chips. To avoid the effect of angular dependence, all the TLD arrays were placed facing directly to the isocentre of the CT gantry, thus making 0° incidence. The measurement range of the TLD chips was from 0.1 pGy to 1 Gy.

After baseline measurements were completed at all measurement points, a pair of lead shielding curtains (Sung Kwang Meditech Co. Ltd, Seoul, Republic of Korea), covering the whole gantry outlet, were placed right in front of the CBCT gantry outlet. The curtains' dimensions were 42 × 60 cm, and the curtains were made from lead vinyl sheeting with 0.5-mm lead equivalent. Two curtains were fixed at the installed bars around the gantry, leaving the inferior and central areas movable. An elbow phantom was placed at the isocentre through the curtains for simulating the actual scan (Figure 3). After the installation of the shielding curtains, all measurements were repeated in the same way as described previously.

Table 1. Mean scattered radiation dose (D_{air}) at different measurement points, with and without the installation of lead curtains

Direction (degrees)	0.5 m		1.0 m		1.5 m		2.0 m	
	No curtains	Curtains	No curtains	Curtains	No curtains	Curtains	No curtains	Curtains
0	159.59	20.05	27.26	8.91	12.48	7.60	8.365	9.71
+45	148.01	8.88	28.67	9.08	16.19	8.87	11.89	7.72
−45	133.06	6.56	30.14	7.22	15.26	6.60	11.91	5.71
+90	18.48	18.64	11.96	11.57	6.84	6.38	5.72	5.93
−90	17.35	18.19	11.35	9.21	7.15	7.91	7.55	8.60

All measured values are in D_{air} (μGy) and were rounded off to two decimal places.

Figure 4. Scattered dosimetry maps (a) before and (b) after shielding with lead curtains. Darker area (black) indicates higher radiation dose. (a) Higher scattered radiation dose is measured at smaller distances. (b) After shielding with the lead curtains, radiation dose is reduced, especially at the smaller distances.

The scattered radiation dose in air (D_{air}) was measured in microgray.¹⁴ Percent decrease in scattered radiation dose was calculated from the dose values without and with curtains, and

the paired t -test was applied. Resulting p -values <0.05 were considered statistically significant. All statistical tests were performed using SPSS® v. 20.0K (SPSS Inc., Chicago, IL).

Table 2. Average dose (D_{air}) and percent reduction in dose, with and without the lead curtains, at different distances

Distance (m)	Without curtains (μGy)	With curtains (μGy)	Percent reduction in dose	p -value
0.5	95.30 ± 66.20	14.46 ± 5.81	84.8	0.000
1.0	21.88 ± 8.99	9.20 ± 1.89	58.0	0.000
1.5	11.58 ± 4.16	7.47 ± 1.50	35.5	0.002
2.0	9.09 ± 2.70	7.53 ± 2.17	17.2	0.117

Table 3. Mean scattered radiation dose (D_{air}) and percent reduction in dose, with and without the lead curtains, for different directions

Direction (degrees)	Without curtains (μGy)	With curtains (μGy)	Percent reduction in dose	p -value
0	51.92 ± 65.39	11.57 ± 5.31	77.7	0.041
+45	51.19 ± 58.75	8.64 ± 1.58	83.1	0.029
-45	47.59 ± 52.32	6.52 ± 1.12	86.3	0.020
+90	10.75 ± 5.73	10.63 ± 5.37	1.1	0.845
-90	10.85 ± 4.57	10.98 ± 4.61	-1.2	0.866

RESULTS

Measured dose values at all measurement points before and after the lead curtains were introduced are shown in Table 1. A scattered radiation map was created based on these data (Figure 4). Mean radiation dose over all measurement points was $34.46 \pm 48.40 \mu\text{Gy}$ without curtains and $9.67 \pm 4.53 \mu\text{Gy}$ with curtains, showing 71.94% overall reduction owing to the curtains. For more detailed evaluation, percent scattered dose reduction at each distance and direction were separately calculated and are shown in Tables 2 and 3.

Without shielding, relatively high scattered radiation levels were measured right in front of the CT gantry. The measured scattered radiation values exponentially decreased with increasing distance from the scanner. The effect of lead shielding curtains became more prominent at smaller distances (Figure 5). Significant reduction of scattered radiation was observed for 0.5, 1.0 and 1.5 m distances, with 84.8%, 58.0% and 35.5% decrease values, which were statistically significant ($p = 0.000$, 0.000 and 0.002 , respectively). At the distance of 2.0 m, the dose reduction was 17.2%, but it was not statistically significant ($p = 0.117$).

For measurement points at the distance of 1.5 m, statistically significant 30% dose reduction was achieved ($p = 0.002$). Shielding had no significant effect on scattered radiation beyond this distance.

In 0° , $+45^\circ$ and -45° directions, radiation dose was significantly reduced by lead shielding by 77.7%, 83.1% and 86.3%, which were statistically significant ($p = 0.041$, 0.029 and 0.020 , respectively). Radiation dose in 90° and -90° directions showed no significant difference before and after the introduction of lead shielding.

DISCUSSION

Since CBCT is based on utilizing ionizing radiation, just as plain radiography and MDCT are, reducing patient radiation dose is an important issue, especially regarding the stochastic effect. Based on molecular knowledge, very small amounts of X-ray radiation can cause permanent change in the DNA base sequence and the likelihood of this effect increases with dose.¹⁵ Therefore, it is important to minimize the unnecessary radiation dose to a patient, even if the radiation dose to the patient is relatively low in extremity imaging using a dedicated CBCT system.

Previous studies have dealt with radiation dose within the FOV.¹⁶ Yet, no standardized methods exist for reducing the patient scattered radiation dose in CBCT imaging. In extremity CBCT imaging, most of radiosensitive organs such as the gonads and the thyroid gland are out of the FOV. Therefore, reducing the scattered radiation might be potentially more beneficial.

Exposure to scattered radiation can be minimized by staying as far away as possible from the gantry isocentre, because scattered radiation decreases exponentially with distance from source. Yet, this method is not suitable for patients taking the CBCT scan.

We considered blocking the whole gantry outlet using flexible radio-absorbable material, making it adaptable to the patient thickness. To the best of our knowledge, curtain-like shielding installed at the CT gantry has not been used in the clinical setting, because it is difficult to use lead shielding curtains in CT imaging with table feed. In extremity imaging using CBCT, the gantry position is fixed during the scan.

Figure 5. The relationship between the distance and the scattered radiation dose (a) before and (b) after shielding with lead curtains. There is a stronger decrease in scattered radiation in the area close to the gantry, where patients are most likely to be positioned during the cone-beam CT imaging.

In this study, the scattered radiation map before installation of lead curtains shows that the radiation dose is higher in the area closer to the gantry opening, as expected. The curtains effectively reduced the scattered radiation dose, showing an average reduction of 71.94%. Furthermore, statistically significant reduction of scattered radiation was achieved in 0°, +45° and −45° directions, with more effective dose reduction at smaller distances. Measured radiation exposure doses in the +90° and −90° directions showed no statistically significant change after the lead curtains were introduced. This is possibly owing to intrinsic radioabsorbable material within the gantry that has already reduced the scattered radiation and to the position of the shield, which does not cover these areas. In other words, a radioabsorbable curtain effectively reduced the out-of-field radiation dose in the area in which a relatively high dose of scattered radiation existed, where most of the patient's body parts, especially radiosensitive organs, are likely to be present. The curtains were easy to install, and opening and closing the curtains took no longer than 1 min. This ease makes the method advantageous in a busy clinical setting.

This study had some limitations. First, three TLD chips per array were used at each spot. More TLD chips would have resulted in more representative results. Second, rear areas of the gantry were not included in this study. However, scattered radiation at the opposite side of a patient seems to have no significance to the patient in extremity scanning using CBCT. Third, there were small gaps between the curtains and the arm phantom. Slightly smaller dose reduction was achieved at 0° than that achieved in 45° and −45° directions. Further dose reduction could be achieved when

minimizing this gap by adequate design modifications. Finally, we did not include the changes in scatter patterns by the patient body. In actual extremity imaging, the patient is positioned in front of the gantry extending the limb of interest into the gantry. When the X-ray passes through the body, both attenuation and scattering would occur, therefore causing out of field effects in radiation dose.

In this study, we found that employing shielding techniques using lead curtains effectively reduced scattered radiation dose in dedicated extremity CBCT, with higher dose reduction closer to the gantry opening, where a patient is most likely to be present. Further studies could be performed to evaluate patient dose and how it differs between areas within the body by placing dosimeters on the various parts of the body phantom.

In conclusion, lead shielding curtains suggest an easy and effective method for reducing patient exposure to radiation in out-of-field regions during dedicated extremity CBCT imaging.

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